ANNUAL REPORT 2004
Constraints on active faulting and diffuse extension in Puerto Rico and the Virgin Islands from GPS geodesy

Grant award number: 04HQGR0091
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Element I
Keywords: GPS contiuous, GPS campaign, regional seismic hazard

NON_TECHNICAL SUMMARY

Data to assess active faulting in Puerto Rico and the Virgin Islands were obtained using Global Positioning System (GPS) geodesy. Analysis of the GPS data is consistent with EW-oriented extension across the island of Puerto Rico. Extension is greater in the west than east. The loci of deformation are not known, but preliminary results indicate that the active structures are likely west of the San Juan metropolitan area. EW-extension that may be accommodated along subaerial faults in Puerto Rico has not previously been recognized and thus not considered in seismic hazard analysis of the island.

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SUMMARY

This project report is submitted in keeping with the requirements as described in the award. The start date of the project was March 1, 2004.

Data to assess active faulting and diffuse extension in Puerto Rico and the Virgin Islands (PRVI) were obtained using Global Positioning System (GPS) geodesy, building on earlier work conducted in PRVI and also funded by NEHRP. Analysis of the GPS data is consistent with westward-increasing EW-extension across PRVI, including EW-extension of a few mm/yr across the island of Puerto Rico. The loci of deformation are not known, but preliminary results indicate that the structures are likely west of the San Juan metropolitan area. EW-extension that may be accommodated along subaerial faults in Puerto Rico has not previously been considered in seismic hazard analysis of the island.

INVESTIGATIONS UNDERTAKEN

Overview and background: Hundreds of earthquakes per year occur within and around Puerto Rico and the Virgin Islands (Figure 1a). The majority of events are small and located offshore. Several large events have occurred in historic time, including the 1916, 1918, and 1943 Mona Passage earthquakes (Ms=7.2, 7.3, and 7.5 respectively), the 1867 Anegada earthquake (Ms=7.3), the 1787 Puerto Rico trench earthquake (M=7.5?) and the 1670 San German earthquake (M=6.5?) (Pacheco and Sykes, 1992). Noting the concentration of both current seismicity and historic events offshore (Figure 1c), several workers proposed a rigid Puerto Rico-northern Virgin Islands block (PRVI) in the northeastern corner of the Caribbean (Byrne et al., 1985; Masson and Scanlon, 1991). The result of our earlier GPS geodetic project funded by USGS-NEHRP does support the existence of a distinct PRVI microplate that translates 2.6±2.0 mm/yr toward N82.5°W±34° (95%). The GPS data also suggest that westward-increasing EW-extension occurs across Puerto Rico and the northern Virgin Islands from zero in the east at Virgin Gorda to 5±2 mm/yr across the Mona Canyon between Hispaniola and western Puerto Rico. EW-extension of 3±1 mm/yr may be accommodated across the island of Puerto Rico. The loci of deformation are not known. Preliminary results indicate that the structures may be west of the San Juan metropolitan area, but additional time on existing sites is necessary to define this and other remaining uncertainties better. EW-extension across PRVI that may be accommodated along subaerial faults in Puerto Rico has not previously been considered in seismic hazard analysis of the island. Past attention has been focused on the Lajas Valley in the southwestern part of the island where seismicity levels are the highest in PRVI (Figure 2).

Most studies of on-land faults in Puerto Rico have focused primarily on structures that cut Tertiary and older rocks (Glover, 1971; Erickson et al., 1990). Prior to the work of Prentice et al. (in press), documentation of features that offset Quaternary units has been limited (e.g. McCann, 1985; Meltzer et al., 1995), leaving most workers to model Puerto Rico as a rigid block (e.g. Masson and Scanlon, 1991). Shallow microseismicity does occur onshore, but the historic record is consistent with major events limited to the offshore region (McCann, 2002). The recognition of Quaternary displacements when coupled with observations of shallow seismicity in western Puerto Rico, however, appears to argue against truly rigid-block behavior. The questions to be answered as part of this project are:

- *What are the permissible displacement rates along the mapped faults given the GPS geodetic results?*
- *Do these rates agree with those derived from the geologic data?*
- *Are these rates consistent with significant and, therefore, possibly destructive earthquakes occurring along subaerial faults within PRVI?*

Because the GPS-derived residual velocities of individual sites in PRVI are small (on the order of a few mm/yr) and the Caribbean reference frame is poorly constrained, errors remain large and limit estimation of discrete fault slip rates. In addition, many of the PRVI sites have short (< 3 year) time series. One of the goals of this project is to reduce the errors significantly by the additional two-years of data to be collected during the tenure of this award. Furthermore, all existing and newly acquired GPS data are being reprocessed using the latest release of GIPSY-OASISII (v. 2.6.4) and an updated Caribbean reference frame. We also are including analysis modules that allow for estimation of tropospheric gradients and rigorous calculation of ocean loading effects and incorporate qualitative estimates of correlated site motion for all sites in the northeastern Caribbean.

While our previous research has unequivocally established that individual site velocities derived from our preliminary GPS dataset have measurable and statistically significant residuals relative to the Caribbean plate (Jansma et al., 2000), the mechanism responsible has not yet been established. The current surface deformation field may be treated as a manifestation of 1) a kinematically distinct microplate between the North American and Caribbean plates; 2) a reflection of elastic strain accumulation along major offshore faults or the subduction interface; or 3) a viscoelastic response to large historical earthquakes. Determining which of these possibilities accounts for the residual velocities is an essential constraint to seismic hazard and risk analysis for the region. For example, in the case of elastic strain accumulation along the plate interface, the potential of large, devastating earthquakes, for which Puerto Rico is not adequately prepared, is significant. The probability of frequent, large events is less likely for a freely translating microplate. Quantitative modeling of the results, therefore, is a key objective of this proposal.

GPS network in PRVI

GPS measurements were first collected in the northeastern Caribbean in 1986 at six locations (Figure 1b) and were re-occupied as part of CANAPE (CAribbean-North American Plate Experiment) in 1994. The network was densified during CANAPE and each subsequent year (Dixon et al., 1998; Jansma et al., 2000; Calais et al., 2002). Since 1994, measurements have been made on subsets of the entire network each year.

The GPS network in Puerto Rico and the Virgin Islands (Figure 2) consists of the original 1994 CANAPE locations (ISAB, PARG, and GORD) plus campaign sites MIRA (Miradero-Mayagüez), ZSUA and ZSUB (San Juan), MAZC (Mayagüez airport), CIDE (UPRM), MONA (Mona island), DSCH (Desecheo island), ADJU (Adjuntas), ARC1 and ARC2 (Arecibo), CCM5 (Ponce), VEGA (Vega Alta), CAJA, (Caja de Muertos Island), FAJA (Fajardo), LAJ1, LAJ2, and LAJ3 (Lajas Valley), SALN (Salinas), VIEQ (Vieques), and ANEG (Anegada, British Virgin Islands) and continuous sites GEOL in Mayagüez, FAJA in Fajardo, UPRR in Rio Piedras, and UPRH in Humacao operated by the Department of Geosciences, University of Arkansas, and PUR3 in Aguadilla maintained by the U.S. Coast Guard. FAJA, UPRR and UPRH were established in 2000 as part of an earlier NEHRP award.

All of the sites in Puerto Rico and its islands (Mona, Desecheo, Vieques, Caja de Muertos) were re-occupied during 2004 as part of this project. Occupations consist of a minimum of 8 hours of data collection each day for 3 days.

GPS data processing

We made several improvements in our GPS data analysis methods using GPS-OASIS II. First, we have now migrated our entire analysis engine from a Sun Ultra60 running Solaris (2.8) to a Dell Precision 650 running RH Linux (WS 3.3). This transition was difficult, given some subtle variations in commands on these systems, but it allowed us to take advantage of the most recent release of GOA-II from JPL (v. 4). Processing speeds have improved by better than 1 order of magnitude: from ~120 s per station-day to <11 s per station-day for a 24 hr absolute point position estimate. In addition, we have undertaken experiments to examine the effect of including ocean loading in our Earth models within GOA-II on the calculated point positions, as we expect the effect to be significant for most of our sites. Ocean loading coefficients for every UARK observation site and all IGS sites analyzed by our lab have been obtained using the model of olfg/olmpp by Scherneck. In addition, we have calculated common mode corrections for all our observations to the September 2004 epoch. These corrections are done off-line and after the initial processing. The final results have yet to be incorporated into our regional analysis or modeling efforts.

Quantitative modeling

We have made considerable progress in the development of kinematic-coupling models to examine elastic strain accumulation and co-seismic displacements in obliquely convergent margins such as the northeastern Caribbean. Our initial efforts used simple 2D elastic models based in the formulation of Savage (1982). While these simple models allow one to explore the control of slab dip angle, degree of kinematic coupling, and locking depth, they are not adequate to address the complex geometry and kinematics of the PRVI subduction zone and Lesser Antilles arc. We have now developed 3D elastic dislocation models for the geometry and plate kinematics of the PRVI, Lesser Antilles, and Middle America subduction zones. This was done using the Department of Energy code DISL (Larsen, 1998), which is based on the formulations of Chinnery (1961), Savage and Hastie (1966), and Mansinha et al. (1971). This code allows one to include a more realistic geometry of a curved subduction interface, by calculating the displacement on a series of linked fault patches. It retains the constraint of determining the displacements for an elastic half-space, however. We have also obtained the license for GeoFEST, which is a 3D finite element code developed by NASA at JPL to investigate a wide variety of geophysical phenomena. GeoFEST will allow us to investigate the effects of visco-elastic and other crustal/mantle rheologies as well as slab texture on the observed surface displacement field. GeoFEST is designed to run in a parallel computing environment, and its successful operation depends on a number of subsidiary software modules. To date, we have obtained the codes and required additional software, but have yet to get all the codes to run successfully on our Linux workstation.

Results

GPS data from the recent 2004 occupations have not yet been processed. The current GPS-derived velocity field thus has not been updated. We anticipate that this will be completed within the next two months. Our reprocessing experiments, which include the effect of ocean loading at a limited number of CGPS sites (including PUR3, GEOL, FAJA, and HUMA), demonstrate that there is significant improvement in the precision of the site positions, lowering our noise estimates on the calculated velocities. The effect is most pronounced in the east and vertical components, with an improvement of 4.3% and 21.6%, respectively. We are now reprocessing all campaign sites with ocean loading on, which should improve the precision of these site velocities as well. Common mode corrections, which are weighted by the inverse square of radial distance from our regional and other far-field CGPS sites, also lowers noise estimates substantially on the campaign sites. We have yet to combine both methods to our entire dataset, but we expect significant reductions in error estimates of all site velocities.

REPORTS IN PRESS

Jansma, P. and G. Mattioli, GPS results fro Puerto Rico and the Virgin Islands: constraints on tectonic setting and rates of active faulting, *GSA Special Paper*, to be published February 2005.

DATA AVAILABILITY

The campaign and continuous GPS data are being archived locally and backed up to DAT and CD. UPRM/UA raw data are not yet publicly available by ftp, because security issues regarding full public access have not been worked out and dedicated computational resources for such public access are not available at this time. Currently, all UPRM/UA GPS data through 2003 have been placed in the UNAVCO archive following the standard procedures established by the GPS community. PUR3 and CRO1 data are available on-line through the standard archives.

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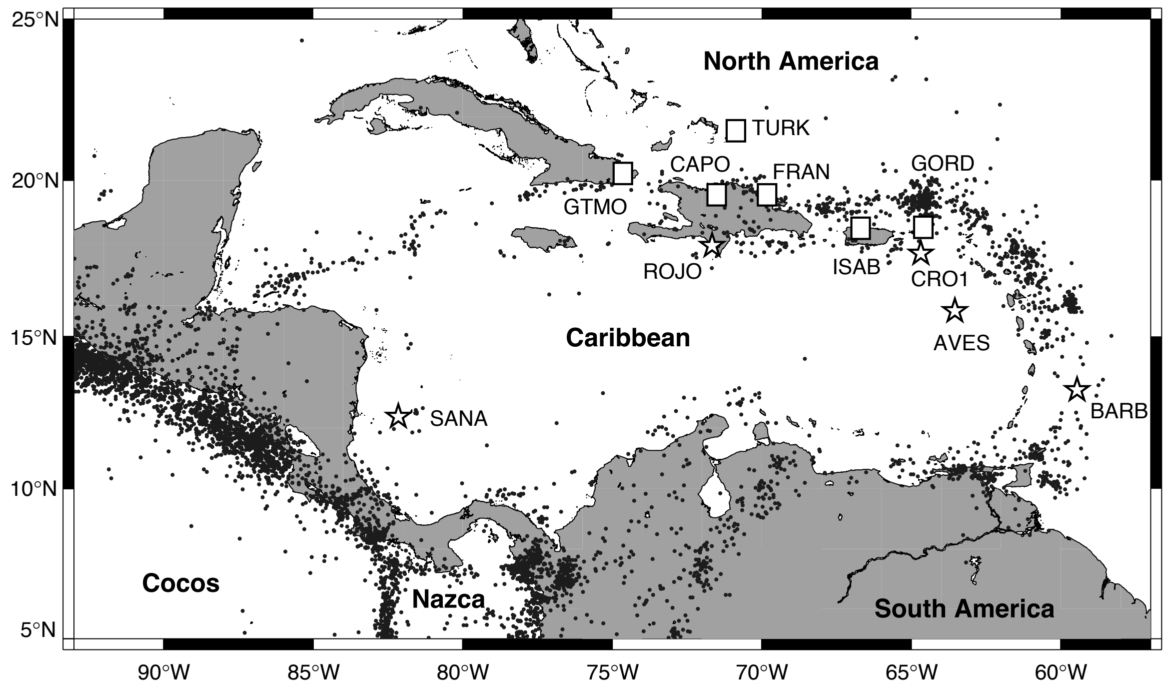
a)



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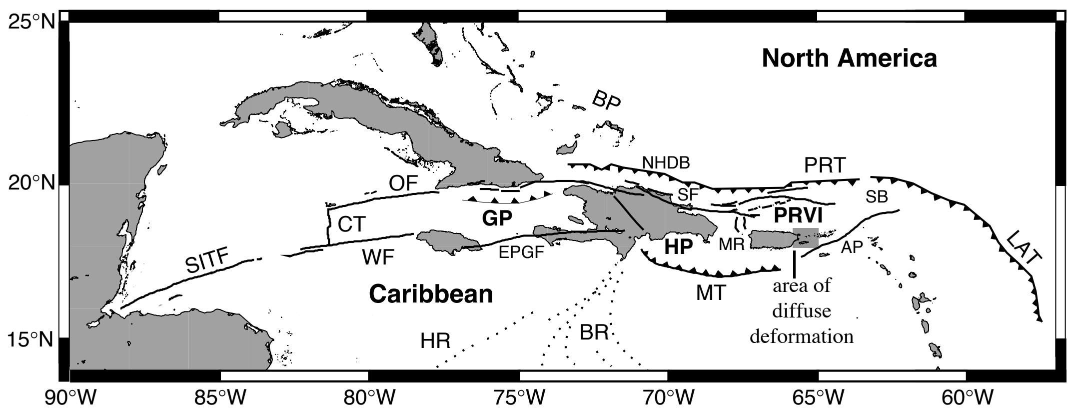

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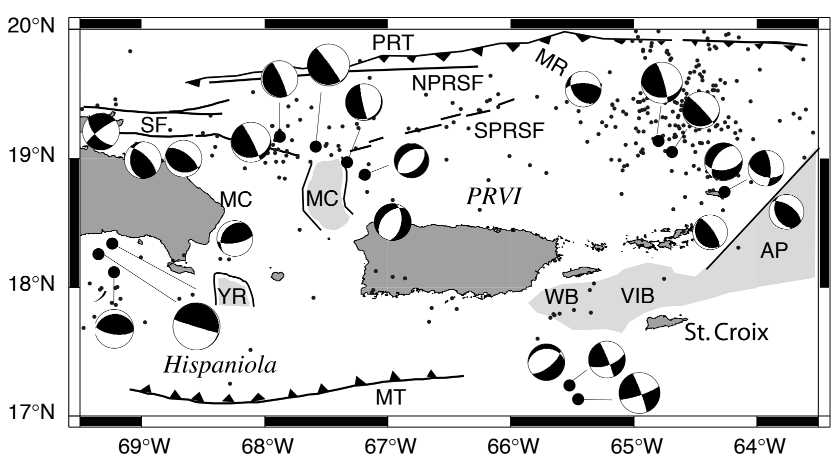

Figure 1: a) Map of the Caribbean plate and regional seismicity. epicenters are for earthquakes above depths of 60 km with magnitudes > 3.5 from 1/1/1967 until 4/28/99 (USGS). The five GPS sites used to constrain the Caribbean reference frame are plotted as stars: SANA-San Andres Island; ROJO-Cabo Rojo, Dominican Republic; CRO1-St. Croix, US Virgin Islands; AVES-Aves Island and BARB-Barbados. Original CANAPE GPS sites are ROJO and CRO1 plus the squares: GTMO-Guantanamo Bay, Cuba; ISAB-Isabela, Puerto Rico; and TURK-Grand Turk, Turks and Caicos. **b)** Map of northern Caribbean plate boundary showing microplates and structures. AP: Anegada Passage. BP: Bahamas Platform. BR: Beata Ridge. CT: Cayman Trough Spreading Center. EPGF: Enriquillo-Plantain Garden Fault. GP: Gonvave Platelet. HP: Hispaniola Platelet. HR: Hess Rise. LAT: Lesser Antilles Trench. MR: Mona Rift. MT: Muertos Trough. PRVI: Puerto Rico-Virgin Islands block. SB: Sombrero Basin. SITF: Swan Islands Transform Fault. SF: Septentrional Fault. WF: Waltfon Fault. **c)** Focal mechanisms for depth < 35 km for eastern Hispaniola, Puerto Rico and Virgin Islands. Sources are the Harvard CMT catalogue, the Puerto Rico Sesimic Network, Deng and Sykes (1995), and Molnar and Sykes (1969). Dots are USGS epicenters (see Figure 1a above). Abbreviations as in Figure 1b. NPRSF: North Puerto Rico Slope Fault. SPRSF: South Puerto Rico Slope Fault. VIB: Virgin Islands Basin. WB: Whiting Basin. YR: Yuma Rift.

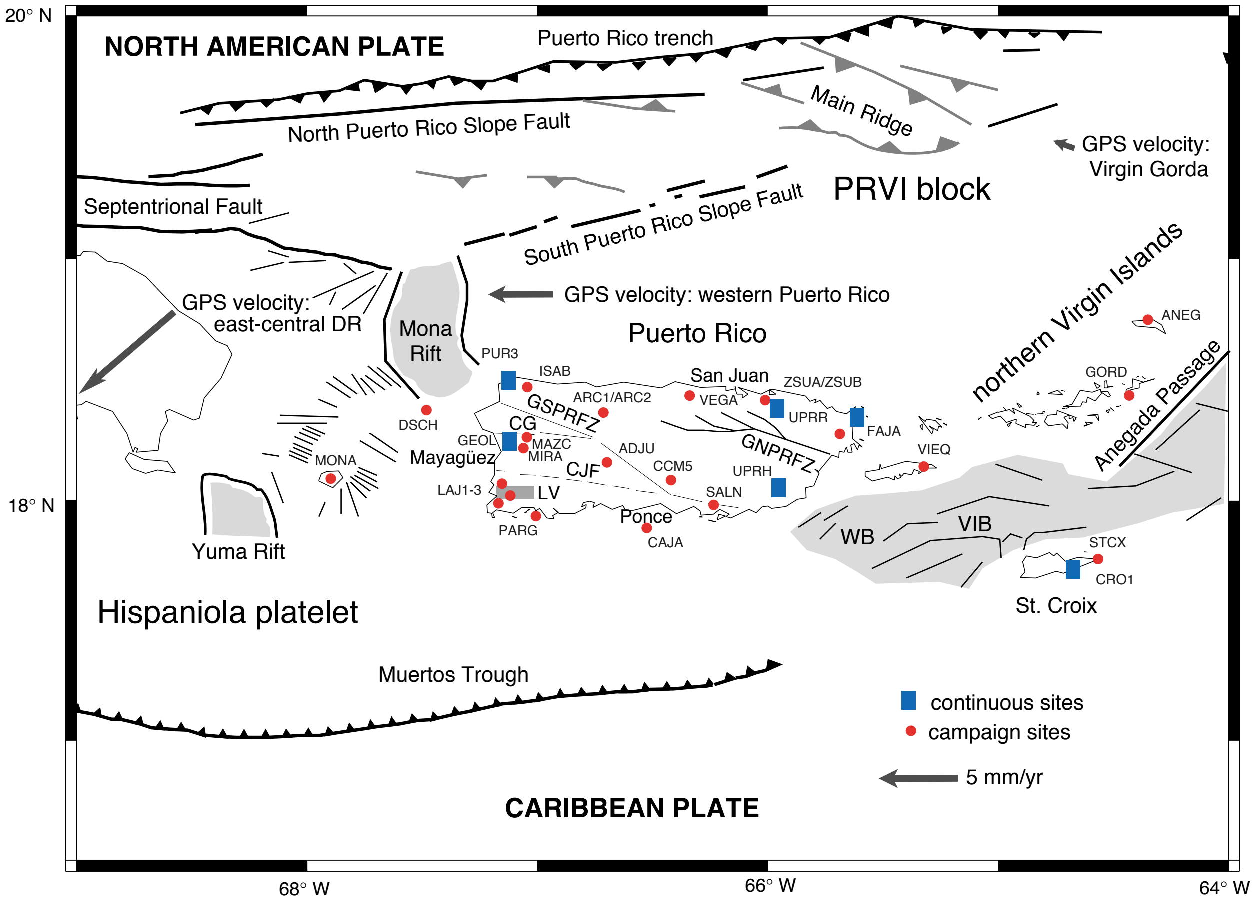

Figure 2: Current mixed-mode GPS geodetic network in the northeastern Caribbean. GNPRFZ: Great Northern Puerto Rico Fault Zone. GSPRFZ: Great Southern Puerto Rico Fault Zone. CG: Cerro Goden Fault. CJF: postulated Cordillera-Joyuda Faults. LV: Lajas Valley (medium gray shaded rectangle in southwestern Puerto Rico). Major offshore structures also are shown. Light gray shaded regions are zones of inferred extension. WB: Whiting Basin. VIB: Virgin Islands Basin. ARrow in Dominican Repubic is GPS-derived velcoity relative to fixed Caribbean for central Hispaniola, south of the Septentrional fault. Arrow north of the island of Puerto Rico is average GPS-derived velocity to the Caribbean for sites in western Puerto Rico. Arrow north of the notherhern Virgin Islands in GPS-derived velocity relative to the Caribbean for site in Virgin Gorda. Length of arrow in lower left corresponds to 5 mm/yr for scale. Error ellipses are not shown for clarity.